Entrainment Mechanisms for Outflows in the L1551 Star-Forming Region

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ABSTRACT

We present high sensitivity ^{12}CO and ^{13}CO J=1→0 molecular line maps covering the full extent of the parsec scale L1551 molecular outflow, including the redshifted east-west (EW) flow. We also present ^{12}CO J=3→2 data that extends over a good fraction of the area mapped in the J=1→0 transition. We compare the molecular data to widefield, narrow-band optical emission in Hα. While there are multiple outflows in the L1551 cloud, the main outflow is oriented at 50° position angle and appears to be driven by embedded source(s) in the central IRS 5 region. The blueshifted outflowing molecular gas extends to the edge of the molecular cloud and beyond the last HH object, HH 256. On the contrary, the redshifted molecular gas terminates within the cloud, short of the most distant HH object, HH 286, which lies well beyond the cloud boundary. The J=3→2 data indicate that there may be molecular emission associated with the L1551 NE jet, within the redshifted lobe of main outflow. We have also better defined the previously known EW flow and believe we have identified its blueshifted counterpart. We further speculate that the origin of the EW outflow lies near HH 102. We use velocity dependent opacity correction to estimate the mass and the energy of the outflow. The resulting mass spectral indices from our analysis, are systematically lower (less steep) than the power law indices obtained towards other outflows in several recent studies that use a similar opacity correction method. We show that systematic errors and biases in the analysis procedures for deriving mass spectra could result in errors in the determination of the power-law indices. The mass spectral indices, the morphological appearance of the position-velocity plots and

integrated intensity emission maps of the molecular data, compared with the optical, suggest that jet-driven bow-shock entrainment is the best explanation for the driving mechanism of outflows in L1551. The kinetic energy of the outflows is found to be comparable to the binding energy of the cloud and sufficient to maintain the turbulence in the L1551 cloud.

Subject headings: stars: circumstellar matter–ISM: clouds–ISM: individual alphanumeric L1551 IRS5–stars: formation

1. Introduction

From the emergence of a hydrostatic core, the collapse of a protostellar core is accompanied by winds and mass loss (Lada 1985) probably driven by magnetospheric accretion (e.g. Koenigl 1991; Edwards et al. 1994; Hartmann et al. 1994). Integrated over time, the effect of a wind from a young star is to blow away the material that shrouds it during its earliest evolution. The discovery of bipolar molecular outflows has been a key to the understanding of this process (e.g. Snell et al. 1980, SLP hereafter). These molecular outflows have dimensions of up to several parsecs, masses one or two orders of magnitude larger than their driving sources, and tremendous kinetic energies (Bally & Lada 1983). Such massive flows must represent swept-up material as the winds, emerging from the star and/or its circumstellar disk, interact with their ambient medium.

One of the important unanswered questions in outflow studies is the mechanism by which the jets/winds emerging from the embedded star/disk entrain and accelerate the surrounding molecular material. Currently there are three scenarios: the "wide-angle wind" model in which a wide-angled magnetized wind expands like a bubble and sweeps up the ambient medium in a momentum conserving manner into the shell at the wind-bubble ambient medium interface (Shu et al. 1991, 1995, 2000; Li & Shu 1996; Matzner & McKee 1999; Lee et al. 2000, 2001). Then there are two types of "jet" entrainment models, the "turbulent" jet entrainment model, in which ambient material is accelerated through a turbulent viscous mixing layer that surrounds the jet formed by Kelvin-Helmholtz instabilities (Canto & Raga 1991; Stahler 1994; Lizano & Giovanardi 1995); and the "prompt" entrainment model in which bow shock formed in the jet head drives material ahead and laterally to the axis of the flow (De Young 1986; Raga & Cabrit 1993; Stone & Norman 1993a,b, 1994; Masson & Chernin 1993; Suttner et al. 1997; Zhang & Zheng 1997; Smith et al. 1997; Downes & Ray 1999; Lee et al. 2001, 2002).

It is essential to distinguish between these models to not only understand the processes

that govern the formation of molecular outflows, but also the nature of the jet/wind launching mechanism and the underlying accretion disk processes. Since it is difficult to observe the jet/wind launching regions directly, the properties of large scale bipolar outflows can shed some light on the nature of their initial conditions. In addition, the energy and momentum deposited by molecular outflows within the molecular cloud can be large enough to power turbulence in the cloud or even disrupt the parts of the cloud. Understanding outflow properties over the entire outflow history is critical in determine their impact on the cloud.

Within the last decade, with the advent of CCD cameras with $20'$ fields-of-view, more than two dozen giant Herbig-Haro (HH) flows with dimensions ranging from 1 to 7 pc have been discovered (Reipurth et al. 1997). HH flows are chains of optically visible shock-excited nebulae which, demonstrate the existence, at least during certain evolutionary phases, of exceedingly well collimated and highly supersonic wind components (e.g. Reipurth et al. 1986). The tremendous size of parsec-scale outflows implies that molecular material is being entrained at parsec-scale distances from the driving source, and thus it may have a significant impact on the kinematics and energy density of a substantial volume of the parent molecular cloud.

Our current estimates of the "typical" outflow properties may be far from accurate, since there is no large homogeneous sample of molecular outflows which have been mapped with good resolution and sensitivity (Richer et al. 2000). Consequently, our current understanding of the processes might be heavily subjective, and biased by a few frequently studied examples. We have been involved in a multi-wavelength study of a dozen or so parsec-scale outflows, complementing narrow-band optical observations with wide-field, sensitive, multi-transitional ^{12}CO and ^{13}CO observations (Stojimirović et al. 2006 in prep.). Here, we present the detailed results of our multi-wavelength study on the L1551 molecular outflow.

The bipolar molecular outflow associated with the L1551 small dark cloud in the Taurus molecular cloud complex, was the first recognized bipolar outflow from a young stellar object (SLP) and is considered one of the best examples of its kind. At a distance of 140 pc (Lynds 1962; Kenyon et al. 1994), the L1551 dark cloud has been the site of many multi-wavelength studies that reveal the dynamical complexity of this low mass star formation region.

Optical images of the L1551 outflow region, show new distant HH object, HH 286 (Devine et al. 1999), making the whole extent of the optical emission in the L1551 flow 1.3 pc. We made sensitive, large spatial extent, high spatial and velocity resolution maps at millimeter and submillimeter wavelengths. Large-spatial extent mapping performed on parsec-scale outflows, allows us to study in detail the entrainment mechanisms by which jets/winds drive the observed molecular flows. With the availability of both ^{12}CO and ^{13}CO data over the full spatial extent of the flow, we are able to take a *full* and proper

accounting of the mass and hence energetics of the outflows in the L1551 system. Comparing optical and millimeter data, we are able to discriminate among entrainment models based on morphological grounds.

2. Observations

2.1. FCRAO CO J=1→0 observations

A full mapping of ^{12}CO and ^{13}CO in the J $= 1 \rightarrow 0$ transition has been performed in several observing seasons over a three-year period with the SEQUOIA receiver at the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope. SEQUOIA (Erickson et al. 1999) is a cryogenic focal plane array designed for the 85–115.6 GHz range, and was upgraded in spring 2002 from the original 16 to 32 pixels. The receiver is configured as a dual-polarized 4×4 array. The telescope's half-power beamwidths are 45″ and 47″ for ^{12}CO and ^{13}CO transitions respectively. The antenna temperatures were corrected for the main beam efficiencies of 0.45 for ^{12}CO and 0.5 for ^{13}CO.

The initial observations were taken in 2001 using raster mapping mode in only the ^{12}CO J=1→0 transition, with channel spacing of 0.21 $\mathrm{km\,s^{-1}}$ and velocity resolution of 0.25 $\mathrm{km\,s^{-1}}$. The data were baselined and convolved to the 22.5″ Nyquist sample grid using CLASS. From 2002, observations were taken using On-The-Fly mapping technique (OTF) and a dual channel correlator (DCC), which allows user to observe 2 frequencies simultaneously with all 32 pixels at SEQUOA, generating 64 spectra for each read of the DCC. The orthogonal polarizations of the SEQUOIA array are averaged to produce spectra with better signal-to-noise ratio (S/N). The OTF data were reduced with the "OTFTOOL" software. OTFTOOL is a suite of tools to inspect, edit, regrid the raw otf data and transform the result into a CLASS or FITS form, developed by M. H. Heyer, G. Narayanan and M. Brewer and available for public usage. Using OTFTOOL, data were examined, channel maps as well as individual spectra were checked for any scanning artifacts, baselined and regridded to the 22.5″ sampled grid. RMS noise weighting was used to combine the data. Regridding takes all of the redundant measurements of the OTF map and constructs the end product - convolved spectra on a regular grid written into a CLASS file. For both ^{12}CO J=1→0 and ^{13}CO J=1→0 transitions, the 50 MHz spectrometer bandwidth setting was used resulting in 50 kHz channel spacing.

Within CLASS, OTF data were smoothed and resampled to the channel spacing of the 2001 ^{12}CO data. The datasets were combined and FITS format files were generated. The resulting velocity spacing is 0.21 $\mathrm{km\,s^{-1}}$and pixel spacing is 22.5″.

The system temperatures (T_{sys}) in our observations range from 400 – 700 K for ^{12}CO and between 200 – 500 K for ^{13}CO. Regions mapped with the higher noise level were repeated, combined and averaged in order to get a constant lower noise level over the whole extent of the map, with resulting mean rms per velocity channel of 0.19 K for ^{12}CO and 0.12 K for ^{13}CO. Antenna pointing and focus were checked every few hours and corrected using SiO masers.

The analysis were done both in the CLASS and IDL software of Research Systems Inc. Detailed studies of the physical parameters characterizing the outflows were performed using IDL.

2.2. HHT CO J=3→2 observations

Submillimeter ^{12}CO and ^{13}CO observations in the J=3→2 transition were carried in December of 2001 and January of 2004 at the 10m Heinrich Hertz Telescope (HHT). HHT's half-power beamwidths are 22″ and 23″ for ^{12}CO, ^{13}CO transitions respectively. Main beam efficiency is 0.5 and forward scatter efficiency of 0.9. As a front-end, the SIS-345GHz receiver was used in single channel mode to achieve the highest sensitivity in that channel. We used the availability of the OTF mapping procedure and mapped 5′×5′ maps with row spacing along declination axis of 6″ and 8″ along RA (scanning rate 10″/sec). L1551 has been mapped in ^{12}CO J=3→2 along the major outflow axis. Single ^{13}CO spectra towards the central YSO and selected lines of sight were also taken. As a back-end configuration, we used all three available AOS's: AOS A, AOS B and AOS C, filter banks and Chirp spectrometer. The two 1 GHz bandwidth AOS's have mean resolutions of 934 kHz for AOSA and 913 kHz for AOSB. The 250 MHz bandwidth of the AOSC has mean resolution of 385 kHz. The AOS's use 2048 element linear CCD's and thus over sample the spectra by about a factor 2 for AOSA and AOSB and a factor 3 for AOSC. The filter bank spectrometer has 3 bandwidth modes: 256 channels of 1 MHz, 256 channels of 250 KHz, and 128 channels of 62.5 KHz resolution, respectively. The final data set is made using only AOSA and AOSB, since AOSC and filter banks experienced noise problems. Spectral resolution is 0.9 $\mathrm{km\,s^{-1}}$. With T_{sys} around 900 K, several repeats resulted in mean rms of $\sim$ 0.1 K for the data presented here.

3. Morphology and Kinematics of Outflows

3.1. Overview of the L1551 Region

Following the discovery of the Herbig-Haro objects, HH 28 and HH 29 (Herbig 1974), and an embedded source, IRS 5 (Strom et al. 1976), in the L1551 dark molecular cloud (Lynds 1962), SLP found a large bipolar outflow centered on IRS 5. Multi-wavelength observations of L1551 cloud conducted through the last 25 years show that the region hosts several young stellar objects in different evolutionary stages and multiple overlapping outflows. What was thought to be a beautiful example of a single bipolar flow turns out to have at least three outflows (Moriarty-Schieven & Wannier 1991; Pound & Bally 1991; Torrelles et al. 1987). Figure 1 shows the blueshifted and redshifted integrated intensity map of our ^{12}CO J=1→0 data overlayed on the Hα image, previously published by Devine et al. (1999).

3.1.1. Young Stellar Objects

There are a number of star-formation sites within the L1551 cloud, some of the most studied are: IRS 5, L1551 NE and the HL Tau region. IRS 5 is a deeply embedded class I source (Strom et al. 1976), with bolometric luminosity of 38 $L_\odot$ (Emerson et al. 1984), hidden from the direct view by up to 150 magnitudes of visual extinction (Stocke et al. 1988). It is a close binary system (Rodríguez et al. 1986, 1998; Campbell et al. 1988; Bieging & Cohen 1985) with components separated by $\sim 0.''35$ (Looney et al. 1997). Located $149''$ east-northeast from the IRS 5 is L1551 NE (Emerson et al. 1984), a Class 0 source with bolometric luminosity of 4.5 $L_\odot$. Radio continuum observations at 3.5 cm suggested (Rodríguez et al. 1995) and later confirmed (Reipurth et al. 2002) that L1551 NE is binary source with $0.''5$ separation. Approximately $6'$ to the north from IRS 5, lies the HL Tau region, with two well-studied T-Tauri stars, HL and XZ Tau. In addition HH 30* and LkHα 358 embedded stars are found in the same HL Tau region.

3.1.2. Jets

Numerous jets have been reported emerging from these three embedded systems. IRS 5 which is believed to be the powering source for the large bipolar molecular outflow has two clearly defined jets (Fridlund & Liseau 1998; Itoh et al. 2000; Rodríguez et al. 2003). The measured position angles are PA=247°±3° for the Northern IRS 5 jet and PA=235°±1° for the Southern IRS 5 jet, using 3.5 cm VLA observations with resolution of $0.''1$ (Rodríguez

et al. 2003). Surprisingly, the position angle of either jet powered by IRS 5 is not aligned with the PA=50° morphology of the molecular CO outflow. However, the Northern IRS 5 jet orientation points to two regions along the edges of the bipolar flow where unusually bright and warm "high-velocity" CS emission has been seen (Plambeck & Snell 1995; Yokogawa et al. 2003). These regions are 4′ west, near HH 102, and 2′ east from IRS 5, at L1551 NE position, and have been hypothesized as working surfaces of the Northern IRS 5 jet. It has been speculated that the formation of L1551 NE was induced by the IRS 5 outflow impact (Emerson et al. 1984; Plambeck & Snell 1995; Yokogawa et al. 2003).

The L1551 NE binary system is observed to drive a jet delineated by [Fe II] emission (Reipurth et al. 2000). The bright [S II] emission HH 454 knots lie within the 2° of the [Fe II] jet. The HH 454 - [Fe II] jet axis has PA $\sim$243°, and we refer to this axis as L1551 NE jet. Proper motion study of the HH 454 knots, show that blueshifted knots are extending toward the southwest and redshifted knots are found toward the northeast from L1551 NE (Devine et al. 1999). This means that if L1551 NE is capable of entraining CO gas in the region, it would be in the same general orientation as the IRS 5 outflow.

In the HL Tau region several optically identified jets of high velocity gas are reported (Mundt et al. 1988). In the CCD images of Devine et al. (1999), at least four flows emerge at different angles from four sources. HL Tau drives a jet at PA $\sim$ 50°, while XZ Tau drives a poorly collimated wind, traced by a set of expanding bubbles imaged by HST towards PA $\sim$ 20° (Krist et al. 1999). The HH 30* source is located 1′.5 south of HL Tau and its optical jet, stretches several arcmin from the source at PA $\sim$ 35/215°. LkHα 358 also appears to drive a flow, probably toward PA $\sim$ 70/250° and is a likely candidate for the origin of HH 265 object (Moriarty-Schieven et al. 2006).

3.1.3. CO and Herbig-Haro Outflows

Figure 1 is dominated by the well known bipolar structure which we will call the main outflow. The main outflow's blueshifted emission lies along PA $\sim$230° and extends 20′ southwest from IRS 5. The main outflow redshifted emission extends 16′ north-east of IRS 5 along PA $\sim$50°. Weak redshifted emission is detected in the far north-east corner of the map and may be related to a further extension of the outflow. In addition to the bipolar outflow symmetric about IRS 5, there are a number of other features that complicate the outflow. First, blueshifted emission is detected near the HL Tau region, well within the red lobe of L1551 flow, and presumably related to outflow activity in the HL Tau region (Moriarty-Schieven & Wannier 1991; Pound & Bally 1991; Torrelles et al. 1987). The most striking feature is the previously discovered redshifted component oriented east-west (EW

flow) that lies north of the blueshifted main outflow (Moriarty-Schieven & Wannier 1991; Pound & Bally 1991). Finally, a blueshifted feature, can be seen extending into the main redshifted outflow lobe to the north-east beyond HH 262 (Moriarty-Schieven & Wannier 1991) and may be connected to the EW flow; an idea that will be discussed in more detail later in the paper.

Devine et al. (1999) reported the discovery of HH 286, making the whole extent of the optical flow 1.3 pc between HH 286 and HH 256. The molecular outflow extends slightly beyond HH 256 in the south-west, however the outflow terminates short of HH 286. The full extent of the CO outflow is approximately $32'$ which corresponds to 1.3 pc at the distance of L1551 cloud. Therefore the spatial extents of the optical and CO outflows, are the same although displaced. Our CO maps extend well beyond HH 286 and in Figure 2 and Figure 3 we show the integrated intensity maps of the ^{12}CO and ^{13}CO J=1→0 emission within the velocity range of the line core. The ^{13}CO J=1→0 map of the line core emission provides our best measure of the distribution of ambient velocity gas. Both figures clearly illustrate that there is no molecular gas at the position of the HH 286. Thus, the molecular outflow ends short of HH 286 because there is no molecular material to be entrained in the outflow.

3.2. Velocity Structure of the Outflows

In Figures 1 and 4 we show the integrated intensity maps of the redshifted and blueshifted outflowing gas in the ^{12}CO J=1→0 and J=3→2 transitions overlayed on an image of Hα emission. The spatial extent of the J=3→2 map is considerably smaller than that of the J=1→0 transition. Although the outflow appears more collimated in the J=3→2 map, this is largely due to the restricted angular extent of the map, which did not cover either the HL Tau or EW outflow regions. The J=3→2 data is primarily useful in probing the inner regions of the main flow at higher angular resolution.

In the following three sections, we will discuss in detail the velocity field associated with the molecular gas within the different flows in L1551. We will discuss the main, HL Tau, and EW outflows.

3.2.1. Main Flow

In Figures 5a and 6a the lowest velocity blueshifted emission is shown. In the larger J=1→0 map (see Figure 5a) one can identify the blue lobe associated with the main outflow, a bow-shaped emission feature associated with HL Tau, and a feature extending north-east

from the main flow toward HH 262. The blue lobe of the main flow has a parabolic shell structure that originates at IRS 5, with IRS 5 embedded within it. This parabolic shell encompasses most of the Hα emission and is best delineated in the higher angular resolution image of the J=3→2 transition of CO seen in Figure 6.

At higher blueshifted velocities the emission becomes more collimated and is confined closer to the outflow axis. The nested velocity structure for the blue lobe of this outflow is very well known. The emission (see Figure 6b,c) predominantly arises in three clumps associated with HH 29, HH 259 and HH 102. For the clumps associated with HH 29 and HH 259, the strongest CO J=3→2 emission lags behind the optically defined shock regions. At the highest blueshifted velocities, (see Figures 5d and 6d), the emission is confined to a region located toward the end of the outflow cavity defined by the optical emission, near HH 259.

The alignment of the HH 454a, HH 29, HH 259, HH 28 with L1551 NE jet axis and the proper motion studies of HH 28 and HH 29 have been used to suggest that they share a common origin in L1551 NE (Devine et al. 1999). If indeed this is the case, it is possible that some of the blue emission we see in the main flow may originate in material entrained by L1551 NE outflow.

In Figures 7 and 8, we show mosaics of integrated intensity channel maps of the redshifted ^{12}CO emission. Besides the main flow, at the lowest redshifted velocities in the larger J=1→0 map, the beginning of the EW flow can be seen. The velocity structure in the redshifted gas of the main flow shows some similarities to that of the blue lobe. Again, there is evidence for a nested velocity structure, however the exact interpretation is complicated by the presence of HL Tau. In Figure 7a one can see an extension of redshifted emission from IRS 5 to the north towards HL Tau. This emission could either be part of a parabolic shell morphology of the main red lobe, or emission associated with the HL Tau outflow. As in the blue lobe, the higher velocity emission is offset from IRS 5 and confined closer to the outflow axis and the highest velocity emission is located near the end of the outflow near HH 262.

Maybe the most tantalizing evidence of molecular emission associated with L1551 NE jet is seen in Figure 8a,b where there is a linear emission feature that arises close to NE and extends for approximately 5′ to the north-east, close to the HH 262. The position angle of this linear feature is ∼ 60° similar to the orientation of the [Fe II] jet driven by L1551 NE (Reipurth et al. 2000). A similar suggestion was made by Moriarty-Schieven et al. (2006). However, the feature could instead be just part of the parabolic shell associated with the main flow from IRS 5. The radial velocity of HH 262 indicates that it is redshifted (López et al. 1998) and that it may be either related to L1551 NE or the outflow associated with IRS 5. Unfortunately, our submillimeter map is not complete in the region surrounding HH

262.

To better show the complex velocity structure within the L1551 outflows, we construct position-velocity (p-V) diagrams by averaging the spectra perpendicular to the p-V axis over a finite width. In Figure 9 we show a p-V diagram constructed from the J=1→0 data with a width of 2′.25. The p-V diagram is aligned along the main outflow axis (at a position angle of 50°) and passes through IRS 5 (at zero offset). Figure 10 shows the p-V diagram constructed from the J=3→2 data along the the same axis with a width of 1′.1.

In the red lobe of the main flow, the velocity structure is relatively simple, with velocity increasing approximately linearly with distance from IRS 5 (Figure 9). Such velocity structure is often dubbed as "Hubble" flow and corresponding feature in the p-V diagram a Hubble wedge. The velocity field within the Hubble wedge shows a systematic acceleration, with both the terminal flow velocity as well as the mean velocity both increasing within the wedge. The terminal velocity in the redshifted lobe is reached near HH 262 at an offset of approximately +11′ from IRS 5, where outflow terminates at all velocities, although cloud emission continues.

The velocity field in the blue lobe of the main flow is more structured than in the red lobe. The inner region of the outflow is shown in the p-V plot of the J=3→2 transition of CO, Figure 10. In this higher resolution p-V diagram, IRS 5 is clearly the symmetry point between the redshifted and blueshifted outflow lobes. In the blue lobe, Hubble wedges associated with HH 29 and HH 259 can be distinguished. The more extended, but lower resolution p-V diagram, constructed from CO J=1→0 transition, shows possible additional Hubble wedge features near HH 29, HH 259, HH 28 and HH 256. The presence of multiple Hubble wedges has been interpreted as due to either episodic or multiple outflow events (Arce & Goodman 2001b). Low velocity outflow emission is detected out to an offset position of -18′, near the edge of the molecular cloud. Thus, the blue flow may be escaping the cloud, while the red flow is stopped within the molecular cloud. The different velocity structure of the red and blue lobes may reflect the differences in the underlying ambient gas distribution.

We also made p-V plots (not shown here) along the L1551 NE jet axis, and these plots are very similar to those shown in Figures 9 and 10. However, in these plots the location of L1551 NE is clearly offset relatively to the symmetry point of the inner redshifted and blueshifted Hubble wedges.

3.2.2. HL Tau Flow

The most prominent feature associated with the HL Tau flow is the clam-shell morphology of the blueshifted CO emission seen in Figure 5a. This feature is centered on the HL Tau jet axis (PA ∼ 50°, Mundt et al. (1990)) and opens toward HH 266. It is likely that this feature reflects the collective impact of several flows on surrounding gas. As mentioned earlier, it is problematic to define the redshifted emission associated with the HL Tau flow since it overlaps main flow's redshifted emission. Figure 7b shows a linear feature extending north-east from the HL Tau region and well aligned with the direction of the HH 30 jet (PA ∼ 31°, Mundt et al. (1990)). The resolution of our J=1→0 data does not allow us to study the details of the HL Tau flow and the J=3→2 map did not extend to this region.

3.2.3. EW flow

In Figure 11 we show a mosaic of integrated intensity maps within successive 4 $km\,s^{-1}$ wide redshifted velocity intervals for the EW flow. We have not overlaid the Hα optical image on the EW flow, because the EW flow extends well beyond the coverage of the optical image. The portion of the EW outflow covered by the optical image, with exception of HH 102, shows no bright optical features associated with the flow. The EW flow has a length of approximately 21′ (corresponding to 0.85 pc at 140 pc distance) and has a relatively large velocity extent ranging from about 8 $km\,s^{-1}$ to 20 $km\,s^{-1}$. This flow is highly collimated at all velocities. The EW flow appears to originate near HH 102 and at successive higher velocities the emission is further offset from the origin. The Hubble flow character to the velocity structure of EW flow is also shown in the p-V plot constructed from the J=1→0 CO data, Figure 12. The p-V plot passes through HH 102 (the zero offset position) and is at position angle 270°. The outflow emission in the EW flow is much weaker than in the main flow, so the p-V plot is much noisier. However, there is evidence for a Hubble flow feature that terminates at a V_{LSR} of +16 $km\,s^{-1}$ at an offset position of approximately 16′.

We speculate that the blueshifted counterpart to the EW red flow is the feature seen in Figure 7a extending into the red lobe of the main outflow. If this feature is related to the EW flow, the redshifted and blueshifted flows are not co-linear and would require that the blueshifted portion of the flow curves northward. The corresponding blueshifted feature that we tentatively identified with EW outflow is not seen in the p-V diagram since it curves north and does not lie along the east-west axis. Figure 1, however, provides a good overview of the possible connection of these two velocity features.

It is intriguing that the high velocity dense gas clumps detected in CS by Plambeck &

Snell (1995) are located near L1551 NE and HH 102. Based on the interferometer results, Plambeck & Snell (1995) and Yokogawa et al. (2003) suggested that NE was formed in a swept-up shell of gas produced by the IRS 5 outflow. The spatial and velocity structure of the CS emission toward HH 102 is similar to that near NE. We speculate, that like NE, the outflow from IRS 5 may have triggered another star formation event within the dense shell of swept-up gas near HH 102. Additional evidence for the interaction of the IRS 5 jet with material in this region is provided by the optical spectroscopy of HH 264, presented by Hartigan et al. (2000). In fact, recently, Moriarty-Schieven et al. (2006) detected relatively strong far-infrared dust emission at 850 μm toward HH 102. Due to insufficient spatial resolution they were not able to conclude if there is any point source within the extended structure. Thus, a newly formed star in this region may be responsible for producing the EW flow and its blueshifted counterpart.

4. Mass and Energetics

The L1551 cloud contains over a dozen young stellar objects concentrated in a region less than 1 pc in diameter and many have associated HH objects or molecular outflow activity, all of which attest to the overall complexity of the L1551 region. We define four areas of interest to study the molecular outflow activity and these are shown in Figure 13. Since the mass distribution along the outflow can be a good indicator of the entrainment mechanism, the idea is to isolate the various outflow components as much as possible. Regions A1 and A2 mark the blue and redshifted lobes of the main outflow. We also separately analyze the blueshifted emission in region A2, which may be associated with the EW outflow. Region A3 delineates the redshifted and blueshifted emission likely associated with HL Tau outflow and region A4 the redshifted emission associated with the EW outflow.

4.1. Excitation Temperature

The excitation temperature (T_{ex}) of the high velocity gas can be estimated from the ratio of ^{12}CO J=3→2 to ^{12}CO J=1→0 line, both available over a significant part of areas A1 and A2. The ^{12}CO J=3→2 data have been spatially convolved to match the spatial resolution of the ^{12}CO J=1→0 data, and ^{12}CO J=1→0 data have been spectrally smoothed to match the 0.9 km s^{-1} velocity resolution of the ^{12}CO J=3→2 data. Using positions where both J=1→0 and J=3→2 data exist and where there is a significant outflow emission, we compute an average spectrum for regions A1 and A2; these spectra and their ratio are shown in Figure 14. At the velocity of the ambient cloud emission the ratio, R = T(J=3→2)/T(J=1→0), has a

minimum value close to the ratio of R= 0.58 predicted for optically thick, thermalized gas at temperature of 10 K.

With the increasing velocity, ratio R increases and becomes relatively constant at outflow velocities. The weighted mean ratio in region A1 from V_{LSR} of 2 to −9 km s^{-1} (blueshifted) is R= 1.69±0.16, and in region A1 from V_{LSR} 10 to 23 km s^{-1} (redshifted) is R= 1.71±0.15. If we assume that the line wing emission is optically thin, and ignore the CMB background term in the radiation equation, the line ratio R between any two transitions, can be related to the T_{ex} as follows:

$$R = \frac{\nu_{J_2}^2}{\nu_{J_1}^2} exp(-\frac{h}{2kT_{ex}}[\nu_{J_2}(J_2 + 1) - \nu_{J_1}(J_1 + 1)]) \tag{1}$$

where J_2 and J_1 are the upper state quantum numbers of the two transitions, respectively; ν_{J_2} and ν_{J_1} are the frequencies for the two transitions. In the case of the ratio R of the J=3→2 and J=1→0 transitions, we derive:

$$T_{ex} = \frac{-27.7}{ln(R/9)} \tag{2}$$

If the emission were optically thin, then the excitation temperature for both regions A1 and A2 would be approximately $T_{ex} = 16.5$ K. However, if the gas is not optically thin, then this ratio provides only a lower bound to T_{ex}. For example, if the optical depth of the J=3→2 line of CO is of order 2, then the observed ratio would imply an excitation temperature of $T_{ex} = 25$ K instead of 16.5 K. In the next section we will show that over the most of the outflow velocity extent, the CO J=1→0 line has moderate optical depths ($\tau = 1$–2), larger in the near line wings and slowly decreasing to higher outflow velocities. It is surprising that the ratio R is relatively unchanged as a function of velocity since the optical depth of the gas decreases at higher outflow velocities. Therefore if there is any change of T_{ex} with velocity, it must decrease from lower to higher outflow velocities. Although the ratio R provides only a lower limit to the excitation temperature, the optical depth is relatively small, so the excitation temperature is unlikely to be grossly underestimated.

4.2. Outflow Mass and Energy

Ideally, the mass of outflowing molecular gas should be determined using an optically thin line such as ^{13}CO or $C^{18}O$. However the emission in the rarer isotopic lines of CO is weak, and thus the spatial and velocity extent to which the outflow could be traced would be extremely limited. In early studies of outflows, the mass was often derived from

^{12}CO without corrections for optical depth. Even after it was recognized that the ^{12}CO emission in the outflowing gas was not optically thin, a single correction for optical depth was used at all velocities. More recently, Bally et al. (1999) and Yu et al. (1999) introduced a velocity dependent opacity-corrected column density approach, that has been used with modifications in many recent observational studies such as Arce & Goodman (2001a). This type of correction is essential for evaluating the outflow mass as a function of velocity.

Since an individual ^{13}CO spectrum does not have the signal to noise to detect the outflowing gas, we need to average over large regions of the outflow. This is the same procedure as employed by Bally et al. (1999) and Yu et al. (1999). In each of the regions previously defined (see Figure 13), we average over the extent of the outflow emission and form an average ^{12}CO and ^{13}CO spectrum. For areas A1 and A2 these average spectra are shown in Figure 15. At velocities where both ^{12}CO and ^{13}CO are detected with at least 3σ certainty, we form the ratio (Figure 15). Similar results are obtained for A3 and A4 regions.

In Bally et al. (1999), Yu et al. (1999) and Arce & Goodman (2001a), they fit the ratio points with a parabolic function in order to extrapolate the optical depth beyond the velocity extent of detectable ^{13}CO emission. Examination of the ratio trends for regions A1 and A2 show that they would not be well fit by a parabolic function. The ratio remains flat in the high velocity wings, implying that the moderate optical depths persist to relatively large velocities. The largest measured ratios are ~ 30, considerable smaller than the expected value of isotopic ratio of approximately 62 for optically thin lines (Langer & Penzias 1993). Instead of a parabolic function, we have fit the ratio with a logarithmic function of the form: $R_{12/13}(v) = A\ln|B - v| + C$, where A, B and C are fitted parameters, and v is the velocity. This functional form fits reasonably well the variations in the observed ratio from the line core to the line wing velocities, Figure 15. We use the logarithmic fits to correct for the optical depth in ^{12}CO line.

We derive the column density of the gas in the outflow by a two step process. Assuming that ^{12}CO emission is optically thin we use the following equation, at each position:

$$N_{12}^{thin}(v) = 1.15 \times 10^{14} \frac{(0.36T_{ex} + 0.33) \int T^{12}dv}{e^{-T_0/T_{ex}}(1 - 0.15(e^{T_0/T_{ex}} - 1))} \tag{3}$$

where T_0 is the value for $h\nu/k$, equal to 5.53 K for the ^{12}CO J=1→0 line, and the velocity is in $\mathrm{km\,s^{-1}}$. The derived optically thin column densities can then be corrected for optical depth effects using the following expression:

$$N_{12}^{thick}(v) = N_{12}^{thin}(v) \frac{62}{R_{12/13}(v)}, \tag{4}$$

where $R_{12/13}$ is determine from the logarithmic fits as a function of velocity, and we assume an isotopic abundance ratio of 62.

The outflow mass as a function of velocity in each pixel is then computed from $M(\mathrm{v}) = 2\mu m_H A N_{H_2}(\mathrm{v})$, where $\mu = 1.36$ is the mean hydrogen mass accounting for He and other molecular constituents, m_H is the mass of the hydrogen atom and A is the physical area of one pixel at the distance of the source. N_{H_2} is the molecular hydrogen column density obtained using the relation $N_{H_2} = 1.1 \times 10^4 N_{12}$ by Frerking et al. (1982) for the Taurus cloud; this result is consistent with more recent determinations, summarized by Harjunpää et al. (2004), for other nearby dark clouds. Table 1 summarizes our results for the mass of the outflowing gas in the various regions previously defined, tabulated for both $T_{\mathrm{ex}} = 16.5$ K and $T_{\mathrm{ex}} = 25$ K. Gas at velocities ≤ 5 km s^{-1} and ≥ 8 km s^{-1} is considered blueshifted and redshifted respectively. The total outflow mass in each area A1-A4, is obtained by summing up calculated mass over all outflow velocities. The total outflow mass in blueshifted and redshifted emission are denoted as BT and RT in the Table 1. The redshifted emission in A2, A3 and A4 do not overlap, so RT is simply the sum of all redshifted mass, momentum and energy of A2 R, A3 R and A4 R. However, there is some overlap of blueshifted emission in A1 B and A2 B (see Figure 13), which we have accounted for in our mass estimate labeled BT.

In Table 1, we also give estimates for total momentum P = MV_{out}, and kinetic energy, E_K = $0.5MV_{out}^2$ in the molecular outflows. We have made no attempt to correct for the inclination of the outflow, so these are only lower limits to the true values of momentum and kinetic energy. Not correcting for the inclination of the outflow, will not affect the mass estimate, since accounting for the tangential velocity will only rescale the velocity axis. The highest uncertainty in the mass estimates, factor of 2, comes from the uncertainty in the N_{H_2} to N_{12} ratio (Frerking et al. 1982). In addition, the outflow mass at the lowest velocities, may have a contribution by the ambient cloud mass. The ambient cloud contamination will decrease with the outflowing velocity. We consider the outflow to start at ~ 1.5 km s^{-1} from the host cloud's mean velocity both for the blueshifted and redshifted velocities. Therefore the effect of the cloud contamination to the low velocity outflow mass is minimal. The choice of the polynomial fit function, is a result of arbitrary choice, and although logarithmic function mimics the behavior of ^{12}CO to ^{13}CO emission ratio better than the parabolic function at the intermediate outflow velocities, it never reaches the thin limit and if ^{12}CO emission becomes optically thin we will overestimate mass at these highest velocities.

4.3. Mass-Velocity Power Law Dependence

It is well established that mass distribution within the molecular outflow has a power-law dependence on velocity, such that $M_{CO}(v) \propto v^{-\gamma}$ (see for e.g. Richer et al. 2000). Observationally the relation is typically obtained by calculating mass per velocity bin and plotting $\log(dM/dv)$ as a function of velocity offset $\log(v_{out})$ relative to the host cloud's mean velocity v_0 ($v_{out} = v - v_0$). In a log-log plot, the slope of the linear fit determines the γ index. The value of γ is an important test for proposed mechanisms of molecular outflow entrainment.

The mass spectra and derived power law indices for regions A1 through A4 are shown in Figure 16. We bin the data in velocity bins uniformly spaced in log scale. The velocity width for each point varies from $0.25 \ \mathrm{km\,s^{-1}}$ on the left side of the plot to $\sim 5 \ \mathrm{km\,s^{-1}}$ on the right side. This has the beneficial effect of increasing the signal-to-noise at high velocities, where the mass is decreasing. Propagation of error is carried out as mass points are binned together, and the error bars for each point are also plotted in the figure. The error bars represent the statistical uncertainty in the mass estimates that comes primarily from the rms noise in each measured spectra and uncertainty in the logarithmic fit parameters. There are also systematic errors such as the uncertainties in the excitation temperature, the functional form of the logarithmic fits to optical depths (Figure 15), and the uncertainty in the N_{H_2} to N_{13} (this latter uncertainty does not affect the slope of the $M(v)$ law). For low velocities, the errors are small enough that the error bars are not visible in Figure 16. Because the statistical errors are very small, but systematic errors could be large, we chose to fit the data to a straight line, assuming uniform weights for all points (Figure 16). If we used the statistical errors in the fit, the uncertainties at low velocities are much lower than at higher velocities, resulting in γ values with formally low uncertainties (typically $\lesssim 0.05$), but with large chi-square values in the fits.

In regions A1 and A2 (the blueshifted and redshifted lobes of the main flow), the dependence of $M(v)$ are best fit with two power-law relations (Figure 16). The break in the power law occurs at $v_{out} \sim 8 \ \mathrm{km\,s^{-1}}$ in A1 one and at $v_{out} \sim 10 \ \mathrm{km\,s^{-1}}$ in A2. The redshifted and blueshifted emission in the HL Tau region (A3) have slightly different $M(v)$ distributions. While the redshifted emission has a broken power law, the blueshifted emission extends to much smaller velocities, and shows a single, steep power-law dependence. The redshifted lobe of the EW flow (see region A4 in Figure 16), and its possible blueshifted counterpart (see the dashed line in region A2 of Figure 16) both show a single, steep power-law dependence. When there is a broken power-law, the average slopes for the low-velocity and high-velocity portions of all outflows in the L1551 region are 1.63 and 2.92 respectively. These values are significantly lower than γ values reported towards other outflows in several recent papers

(see §5.2 for a more detailed discussion on this point).

4.4.   Cloud Mass and Energy

We determine the cloud mass by using the ^{13}CO map. The line center optical depth at each point in the map is derived from the ^{13}CO peak temperature. The excitation temperature is obtained at each position by solving the radiative transfer equation for the excitation temperature, assuming ^{12}CO line to be optically thick. The column density for the ^{13}CO J=1→0 transitions is calculated at each map point in the velocity range of 5 to 8 $km\,s^{-1}$. We find, the total mass of the cloud using this method to be 110 $M_\odot$, and is reported in Table 1 in the AC (ambient cloud) row. The newly estimated cloud mass is larger than the previous estimate of Moriarty-Schieven & Snell (1988) and in agreement with Sandqvist & Bernes (1980). The kinetic energy of the cloud is assumed to be the turbulent energy of the cloud, and is estimated using $E_{\mathrm{turb}} = 3/(16ln2)M_{\mathrm{cloud}}\Delta v^2$. Mean turbulent velocity of the ambient gas, $\Delta v = 1.2$ $km\,s^{-1}$ is determined from several ^{13}CO line profiles in the cloud, as the full line width at the half maximum. We find that kinetic energy of the L1551 cloud is $\sim 8.5 \times 10^{44}$ ergs.

5.   Discussion

5.1.   Entrainment Mechanism for CO Outflows in L1551

The combination of optical Hα, millimeter and submillimeter CO data provides a more complete picture of the structure and kinematics of the molecular outflows in the L1551 region, allowing us to better investigate the driving mechanism of molecular outflows. Currently the two most promising models of entrainment of outflows are the jet-driven bow-shock model and the wind-driven shell model. Numerous hydrodynamic and analytical models have treated both types of entrainment mechanisms and predict distinct morphologies for the appearance of the integrated intensity maps, position-velocity maps, and the mass-velocity power law indices (for examples see Smith et al. 1997; Zhang & Zheng 1997; Lee et al. 2000, 2001; Ostriker et al. 2001).

One of the most distinctive observational characteristics of molecular outflows is the power-law dependence of flow mass with velocity, $M_{CO}(v) \propto v^{-\gamma}$. Usually, log(dM/dv) versus log(v) has a linear dependence, with a single power law index γ ranging from about 0.5 to 3.5, with the majority of observations indicating $\gamma \sim 2$ (Richer et al. 2000). At velocities larger than 10 $km\,s^{-1}$ from the ambient cloud velocity, many outflows show a break in the

power-law with higher velocities showing a steeper slope. The break at higher velocities might indicate that there are two distinct outflow components, perhaps corresponding to a recently accelerated component, and a slower-moving swept-up component. It also appears that the low-velocity power-law index of ~ 2 is the same for low-mass as well as high-mass objects, indicating that some common acceleration mechanism operates over several decades of stellar luminosity (Richer et al. 2000). There is also some indication, especially for high-mass objects that the slope, γ steepens with age (Richer et al. 2000). Thus, observations of γ and the occurrence of breaks in the power law could thus be used to constrain the driving mechanism in a given outflow. In turn, the trends seen in the mass versus velocity ($M(\mathrm{v})$) power laws of observed outflows can be used to refine the theoretical models of outflow entrainment. Accurate determination of the value of γ is thus quite important.

Numerical simulation of both jet- and wind-driven models (Lee et al. 2001) show that the power law index in $M(\mathrm{v})$ plots for jet-driven bow-shock systems ranges from 1.5 to 3.5, while the wind models yield smaller value of γ in the range of 1.3 to 1.8. In the jet-driven models, γ is a strong function of inclination, with lower values of γ obtained when the outflow has larger angles of inclination to the plane of the sky. Zhang & Zheng (1997) show that power-law with break is produced for the jet-driven entrained gas.

Jet-driven bow-shock models show Hubble-law like features in the position-velocity plots with the highest velocities at the "hot spots" (head of the jet) and decreasing velocity trend toward the source (wings of the bow shock). The p-V structure is associated with the broad range of velocity near the bow tip while there is a small and almost constant velocity in the bow wings, often producing a convex spur structure along the jet axis at the highest velocities (Lee et al. 2000, 2001). Figure 20 in Lee et al. (2000) shows a strong dependence on inclination angle for the p-V diagram structure in bow shock model. In the case where several bow shocks are driven because of the presence of a pulsed jet, several spur structures can be seen in the p-V diagram. (see Fig. 7, Lee et al. 2000, HH 212). On the other hand, wind-driven entrainment mechanism do not show any evidence for spur features in the p-V plots; the p-V plots are typically parabolic in shape with the vertex of the parabola coincident with the location of the source. The morphology of the shape is somewhat inclination dependent, but the p-V plots are quite distinctive in appearance from that produced by jet-driven models.

In § 4.3, we report our results for the mass-velocity power laws. Our main result is that when there is a break in the power law, the power law slope for low velocities is shallow, $\gamma \lesssim 2$. The power law index for high velocities is $\gtrsim 3$ (see Figure 16).

The main CO outflow oriented at $50°$ from IRS 5 shows mostly jet-driven bow-shock features, but also shows some morphological features seen in wind-driven flows. The $M(\mathrm{v})$

plots for the blue and redshifted lobes (regions A1 and A2) of the main IRS 5 outflow show a power-law break as predicted by a jet-driven flow (see Figure 16). The millimeter and submillimeter p-V plots for IRS 5 (Figures 9 and 10) show multiple Hubble-law wedges, with spur-like features at the highest velocities (see especially the submillimeter data in Figure 10). The blueshifted side of the CO J=1→0 p-V plot (Figure 9) might be interpreted as a parabolic feature, or it may be two Hubble like wedges adjacent to each other. But the redshifted side shows no evidence for any parabolic structure. A single convex spur-like feature is seen in the p-V plot on the redshifted side. The channel maps in Figures 5 through 8 show a morphology where the highest velocity emission is the most collimated, and is along the projected jet axis, and is often seen in the vicinity of HH objects, probably highlighting the interaction regions of shocks at the heads of the bow-shock interfaces of the underlying jet with the swept-up molecular material. The overall spatial morphology of the low-velocity gas in blue and redshifted lobes is roughly parabolic (see Figures 5 through 8), with the slower swept-up gas manifesting itself as limb-brightened shell-like features. It has been proposed that the entrainment mechanism itself may evolve in outflows, with the early stages being a collimated jet-driven flow, which in later stages evolves into very wide-angle wind (Velusamy & Langer 1998; Richer et al. 2000). If so, the characteristics of both jet-like and wind-driven entrainment for the IRS 5 flow might be indicative of its relatively evolved stage as an outflow.

The EW flow on the other hand shows only jet-like features. The flow is highly collimated (see Figure 11), the $M(v)$ plots for both the redshifted western component and the possible blueshifted component (in the redshifted lobe of IRS 5 flow) show single sloped power law with steep power-law indices ($\gamma = 3.1$ and 4.5 respectively) indicative of jet-driven bow-shock entrainment. The p-V diagram for the EW flow (Figure 12) shows no parabolic features, but a low-intensity Hubble-like wedge ending in a broad spur at the tip. It is noteworthy that the $M(v)$ plot (see Figure 16) for the EW flow is quite distinct from that of the IRS 5 flow. As suggested earlier, it is possible that the EW flow is dynamically younger flow, driven from an hitherto undetected source close to the location of HH 102 at about the location of the 850 μm peak emission seen by Moriarty-Schieven et al. (2006). Unlike the IRS 5 flow, no optical counterpart HH objects have yet been detected along the EW jet axis.

5.2. Systematic Effects on Mass Spectra Slopes

The power law indices at both low and high velocities that we derive for L1551 are not as steep as some recent determinations of γ in other outflows. For example, other groups have found $\gamma > 3.5$ (single power-law) for Circinus (Bally et al. 1999) and Barnard 5 (Yu

et al. 1999), broken power-law with $\gamma \sim 2$ (low velocities) and $\gamma \gtrsim 5$ (high velocities) in OMC-2/3 (Yu et al. 2000), broken-power law with $\gamma \gtrsim 3$ (low velocities) and $\gamma > 6$ (high velocities) for HH 300 (Arce & Goodman 2001a), broken power-law with $\gamma \sim 2.2$ (low velocities) and $\gamma \gtrsim 3.5$ (high velocities) for PV Cep (Arce & Goodman 2002). These recent studies have reported systematically steeper power law indices than reported before, and when accompanied with a break in the power law, much steeper slopes at higher velocities. One common feature of these recent results with larger values of γ was that they employed a velocity-dependent opacity correction. In this work, we have employed a similar velocity-dependent opacity correction approach, but we derive smaller values of γ. Our results here seem to counter this trend towards larger values of γ. Does this indicate that L1551 is a different kind of outflow system than these other outflows? There are several systematic effects in the derivation of mass-velocity spectra that if not properly accounted for, can result in errors in the determination of γ. Below we consider these systematic effects to explain the difference in γ derived in this paper compared to some recent determinations of this quantity.

(1) The overall mass estimate at all velocities can be affected by the size of the outflow mapped. If high velocity portions of the outflow are missed in the mapping, the derived γ would be an over-estimate. Our study as well as the studies of Bally et al. (1999); Yu et al. (1999, 2000); Arce & Goodman (2001a, 2002) have mapped a larger area of the outflow lobes than most previous studies (primarily due to the higher sensitivities of receivers and the advent of OTF mapping). The size of the mapped region is probably not the cause of difference in derived value of γ.

(2) The exact form for the functional fit to the velocity dependent opacity correction can affect the slopes of the mass spectra. In the studies of Bally et al. (1999); Yu et al. (1999, 2000); Arce & Goodman (2001a, 2002), parabolic fits were used to extrapolate the value of the ratio (^{12}CO/^{13}CO) beyond values where the ratio is well determined. We use a logarithmic function (see Figure 15) instead. The logarithmic function is a better fit to the variation of the ratio seen in our data, but it tends to be a more slowly varying function with velocity than the parabolic fits. This makes for larger corrections (more mass) for the higher velocity points, which in turn makes the mass spectral slopes shallower. It should be noted that, compared to earlier studies, our data have higher sensitivity even at higher velocities from the systemic velocity, and this leads to a better constraint of the ^{12}CO/^{13}CO ratio to much higher velocities. The variation of optical depth of CO in molecular outflows with velocity has not been well determined to high velocities. However, when high signal-to-noise ratio spectral data have been obtained towards high velocity molecular outflows, the ratio of ^{12}CO/^{13}CO seems to be slowly varying with velocity (Snell et al. 1984), as is seen in our study. As another example, in Figures 7(c) and 7(d) of Arce & Goodman (2002), it is seen

that the ratio of ^{12}CO/^{13}CO seems to be actually flat, however, the authors use a parabolic fit. A parabolic fit is a much faster extrapolation function in velocity and predicts that the gas gets to the optically thin limit at lower velocity offsets from the systemic velocity.

(3) Previous studies of mass spectra apply a method of only using data which exceeds a specified threshold in rms value of T_A^*. For example, Arce & Goodman (2001a) used a 2σ threshold, while Bally et al. (1999) used a 1σ threshold. Figure 17 shows the effect of using a rms threshold in the determination of the mass spectra. The rms thresholding method preferentially rejects points at higher velocity channels, since those points have the lowest signal to noise, and hence do not meet the rms threshold. Because of this, mass is under-estimated preferentially at higher velocities, thereby artificially steepening the mass-spectral slopes.

The velocity-dependent optical depth correction used in Bally et al. (1999); Yu et al. (1999, 2000); Arce & Goodman (2001a, 2002) as also in this work does result in more accurate mass determinations. In particular, not using the correction results in an under-estimation of the mass at especially lower velocities, artificially giving low mass-spectra slopes. On the other hand, care must be taken with the functional form of the fit of optical depth with velocity. Figure 17 shows the importance of using all the data or at least being aware of the effect that posing a specified threshold in rms value will have on mass spectrum.

5.3. Combined Effect of the Outflows on the Cloud

The mass for the L1551 cloud estimated from the fully sample ^{13}CO map at line core velocities of 5 to 8 km s^{-1} is ~ 110 M$_\odot$. Outside of the line core velocities, the total mass estimated in the outflow is ~ 5.3 M$_\odot$ for $T_{\mathrm{ex}} = 16.5$ K or ~ 6.7 M$_\odot$ for $T_{\mathrm{ex}} = 25$ K. Therefore the mass in the outflow is approximately 5-6.5% of the mass of surrounding cloud, depending on the adopted value for the T_{ex}. The total momentum and energy carried by the outflow, estimated from only the line of sight (radial) velocity, is 20 $M_\odot$km s^{-1}and 1.5×10^{45} ergs, respectively. It it usually assumed that the L1551 outflows have small inclination angles relatively to the plane of the sky, so there is a large inclination correction to the momentum and energy determinations. However, since the inclination angle is extremely uncertain, we will use the values quoted above as lower limits to the true values.

Many authors suggest that outflows provide a mechanism to regulate star formation by removal of the gas from star-forming regions, especially in the regions that lack massive stars (eg. Matzner & McKee (2000), and references therein). For the outflow entrained gas, to escape from the cloud, it must be moving at least at the escape velocity. Using a mass of 110

$M_\odot$ and ~ 1 pc radius for the cloud, the escape velocity is calculated to be ~ 1 km s^{-1}. If all of the momentum of the outflowing molecular gas was transferred to the cloud uniformly, then the gas would not escape. However, since outflows are highly collimated, momentum is transferred non-uniformly and much of the present outflowing molecular gas is likely to escape, unless it is slowed down by encounters with ambient gas. Our observations suggest that in fact the main blue lobe has broken out of the cloud near HH 256, and that their is insufficient column density of gas to slow the gas as it escapes. However, in the main red lobe, the molecular outflow is still well within the boundaries of the cloud and it remains to be determined if there is sufficient column density of gas to halt the outflow. Thus, the outflows are unlikely to disperse the entire cloud, but in local regions will be a major agent for disruption.

The total binding energy of the cloud is given by $\sim GM_{\rm cloud}^2/R$. Using a cloud mass of 110 $M_\odot$ and ~ 0.5 pc for the cloud radius, we find the binding energy to be 2×10^{45} ergs. Thus, the energy of the outflow 1.5-2$\times10^{45}$ ergs, is comparable to the binding energy of the cloud, even if no correction for the inclination angle is made. It has been suggested that parsec-scale outflows can be a source of energy to replace the energy dissipated in turbulence and thus provide the power to maintain the magnetohydrodynamic (MHD) turbulence (Li & Nakamura 2006). The rate of turbulent energy dissipation can be estimated from equation (7) in Mac Low (1999). Assuming a cloud mass of 110 $M_\odot$ and a mean turbulent velocity dispersion of 0.45 km s^{-1} (estimated from the ^{13}CO line width), we find that the energy dissipation rate of turbulence in L1551 cloud is 0.003 $L_\odot$. Thus, if even a small fraction of the outflow energy could be coupled into cloud turbulence, the outflow could sustain the turbulence for over a million years, much greater than the lifetimes of molecular outflows.

We have shown that the molecular outflows contain substantial kinetic energy. However, the effect outflows have on their parent clouds depends on the efficiency in which momentum and energy can be transferred from the outflowing molecular gas to the surrounding cloud material. Currently, the observations are insufficient to answer this question, and there are no good theoretical models that address the effect outflows have on disruption of the cloud or on their role in replenishing the reservoir of turbulence energy in clouds. However, our work and several recent studies of parsec scale outflows, suggest that young stars, through the combined effect of their outflows, may have an important impact on the dispersal of their parent molecular cloud and to power turbulent motions.

5.4. Sequential Star Formation in L1551?

The L1551 molecular core is an active star-forming region which harbors at least 2 small clusters of protostars, one centered in the IRS 5 and L1551 NE region, and another in the HL Tau region. These two mini-clusters are clearly undergoing active star-formation characterized by HH objects, optical and near-infrared jets. In addition, multi-wavelength surveys in mid infrared (Gålfalk et al. 2004), X-ray (Favata et al. 2003), optical and near-IR (Briceño et al. 1998), optical spectra (Gomez et al. 1992), and in Hα (Garnavich et al. 1992) have shown that the whole L1551 molecular core is surrounded by a halo of young stars in the Class II stage or older, indicating that star-formation activity has been ongoing in this region for at least a few million years. Here, we explore the possibility that the current epoch of star-formation activity in L1551 may be the result of sequential star-formation induced by the effects of the multiple outflows in the system.

The protobinary system in IRS 5 has two active jets. The current direction of either of these jets is not aligned with the $\sim 50°$ oriented main CO outflow in this region, the latter being driven by the source(s) at IRS 5. At least at some point in the past, the predominant direction of the jets from the IRS 5 system was probably aligned with the bulk molecular outflow direction in L1551. It has been suggested that L1551 NE was formed in the swept-up shell of gas produced by the IRS 5 outflow (Plambeck & Snell 1995; Yokogawa et al. 2003). L1551 NE is itself a multiple stellar system, and possesses optical jets, and is thought to power a large-scale HH flow including HH 454, HH 28 and HH 29 (Devine et al. 1999; Hartigan et al. 2000). The evidence for a CO outflow from L1551 NE is not as clear-cut despite many observational attempts to delineate the outflow, mostly because of its similar alignment and close proximity to the main flow from IRS 5. The high angular resolution interferometric observations of Plambeck & Snell (1995) and Yokogawa et al. (2003) show two symmetric CS structures, one eastward from IRS 5 near L1551 NE, and thought to be responsible for the formation of L1551 NE, and another near HH 102. As discussed before, with the presence of a 850 μm dust-continuum clump near HH 102 (Moriarty-Schieven et al. 2006), it is tempting to suggest that a similar triggering mechanism can be attributed to the EW outflow. It is possible that the same bipolar jet streaming eastward started the star-formation process in L1551 NE, and streaming westward, started the star-formation process in the clump near HH 102. This new driving source near HH 102 is maybe responsible for the EW flow. This new protostar is obscured in the HH 102 region, and the highly collimated CO outflow, and the jet-like characteristics of the EW flow are indeed consistent with a relatively young protostellar system. Follow-up high angular resolution observations of the HH 102 region would allow us to probe the possibility that there is a new embedded source near HH 102.

The evidence for sequential star-formation activity is further strengthened by some recent observations of the L1551 region. A new pre-protostellar clump, dubbed L1551-MC has been discovered near HH 265 Swift et al. (2005) using NH_3 observations, and later confirmed (Moriarty-Schieven et al. 2006) by 850 μm continuum observations. L1551-MC is located at the edge of HH 265, which may be a HH object at the end of a jet arising from a driving source within the HL Tau complex (see Figure 17 of Moriarty-Schieven et al. (2006)). It is possible that the next generation of star-formation in the L1551 molecular cloud could occur at the L1551-MC region.

6. Summary And Conclusions

All L1551 molecular outflows have been mapped at high sensitivities in the ^{12}CO and ^{13}CO J=1→0 transitions. Follow-up submillimeter observations in ^{12}CO J=3→2 emission towards a good fraction of the L1551 outflow system were carried out as well. The millimeter and submillimeter data are combined with large-scale, narrow band, optical Hα images in order to perform a detailed study of the outflows in L1551. The main conclusions of the paper are summarized below.

1. The full extent of the main CO outflow is 32′ (1.3 pc), and is oriented at $\sim 50°$ position angle. The molecular outflow extent is similar to the optical extent of the flow seen by Devine et al. (1999). Outflowing molecular material extends well beyond the last known HH object, HH 256 in the south-west, but stops short of HH 286 in the north-east. Our molecular line maps indicate that HH 286 has completely exited the L1551 cloud.

2. Most of the CO molecular outflow appears to be driven by source(s) in the IRS 5 region. Some features, especially in the redshifted lobe of the outflow may be attributed to outflows originating in L1551 NE and the HL Tau region.

3. Our maps cover a much larger extent of the collimated redshifted EW flow. The EW flow is ~ 0.82 pc in length, and is ~ 0.15 pc in width. In contrast to earlier studies, the sensitivity in our data reveals that the EW flow extends to high velocities (6.5 $\mathrm{km\,s^{-1}}$ to 20 $\mathrm{km\,s^{-1}}$). It is suggested that a smaller extent blueshifted component seen in the main northwestern redshifted lobe is the blueshifted counterpart of the EW flow, and that the driving source for the EW flow is close to the location of HH 102.

4. We refine the procedure of velocity-dependent opacity correction adopted by recent authors to obtain a more accurate determination of outflow mass with velocity. The

resultant mass-spectral power law indices are lower (less steep) than recently obtained indices towards other outflows. We attribute this systematic difference in power-law index to the better quality of our data, and the more careful approach we use in calculating mass. The resulting mass of the L1551 molecular cloud core is ~ 110 M$_\odot$ and the combined mass of the outflows in L1551 is ~ 7.2 M$_\odot$.

5. Even for no inclination angle correction, and lower T_{ex} assumption, the kinetic energy of the outflow is comparable to the binding energy of the cloud and there seems to be enough outflow energy to maintain turbulence in the cloud. Therefore the parsec scale outflow in L1551 has a potential of making a strong impact on the cloud's evolution and fate.

6. Multiple lines of evidence from $M(v)$ spectral indices, position velocity plots, and morphological appearance of our multi-wavelength data indicate that the EW molecular outflow is a good example of jet-driven bow shock entrainment. The main molecular outflow in L1551 shows evidence for entrainment from both jet-driven and wind-driven mechanisms.

7. We suggest that new stars are being triggered to form in the L1551 system as a result of the effects of the multiple outflows in the region.

Facilities: FCRAO, HHT

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Fig. 1.— Integrated intensity ^{12}CO J=1→0 emission in L1551 overlayed on optical Hα data. Blueshifted gas is integrated in velocity range of -20 to 5 km s^{-1}. Contours start at 3σ and are 1.5, 3, 4.5, 6, 9, 12, 16, 20, 24, 28, 32, 36, 40, 44 K km s^{-1}, plotted in blue. Redshifted emission is integrated in velocity range of 8 to 20 km s^{-1}. Contours start at 4.5σ level and are 1.5, 3, 5, 9, 12, 15, 18, 22, 26, 30, 34, 38, 42, 46 K km s^{-1}, plotted in red. Symbols for different driving sources are introduced: filled square for L1551 IRS 5, filled circle for L1551 NE, filled triangle for HL/XZ Tau system and cross for various HH objects. Notation will be kept on following figures. CO mapping was performed well beyond the borders of the optical image, reaching a degree squared centered on IRS 5 source. Dark spots in the optical image are shock-excited gas, usually associated with various HH objects.

Fig. 2.— Integrated intensity of the ^{12}CO J=1→0 line within core velocities from 5 to 8 km s^{-1} and overlayed on Hα data. Contours are 1.5, 3, 4.5, 6, 9, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60 K km s^{-1}, where 1σ level corresponds to ~ 0.2 K km s^{-1}. ^{12}CO J=1→0 map in line core velocities shows the distribution of the molecular gas in the L1551 cloud. The straight thick lines in the figure outlines the borders of observed CO map.

Fig. 3.— Integrated intensity of the ^{13}CO J=1→0 emission overlayed on optical Hα data. Gas is integrated in line core velocity range of 5 to 8 km s^{-1} and the lowest contour is at 1 K km s^{-1} increasing in steps of 1 K km s^{-1}. 1σ level corresponds to 0.1 K km s^{-1}. ^{13}CO J=1→0 probes the higher column density regions within the cloud. The edges of the OTF map are shown here in straight thick lines.

Fig. 4.— Integrated intensity ^{12}CO J=3→2 emission in L1551 shown in dotted line for blueshifted lobe and in solid line for red shifted emission overlayed on optical Hα data. Blueshifted gas is integrated in velocity range of -20 to 4 km s^{-1} and the lowest contour is 5 K km s^{-1} ($\sim 10\sigma$ level) increasing in steps of 7 K km s^{-1}. Redshifted emission is integrated in velocity range of 8 to 20 km s^{-1}. Lowest contour is at 5 K km s^{-1} (15σ level) increasing in steps of 5 K km s^{-1}. Symbols for different driving sources and jets are kept as on Figure 1.

Fig. 5.— Channel-maps of the ^{12}CO J=1→0 blueshifted integrated intensity emission. The CO line is integrated within 4 km s^{-1} velocity bin, starting from 5 km s^{-1}. The velocity range used for the integration is given in each panel. The contours start at 2 K km s^{-1} (10 σ) and go in steps of 2 K km s^{-1} in panels "a" and "b". In the lower panels the step is changed to 1 K km s^{-1}. In each panel, embedded stars are noted with square (IRS 5 at (0,0) position), circle (L1551 NE) and triangle (HL/XZ Tau) and crosses are for HH objects. In the "d" panel we assign each cross to the corresponding HH object. The same holds for the next figure.

Fig. 6.— Channel-maps of the ^{12}CO J=3→2 blueshifted integrated intensity emission. The CO line is integrated within 4 km s^{-1} velocity bin, starting from 5 km s^{-1}. The velocity range used for the integration is given in each panel. The contours start at 2 K km s^{-1} (10 σ) and go in steps of 5 K km s^{-1} in the panels "a" and "b" and in the other two panels step is changed to 2.5 K km s^{-1}.

Fig. 7.— Channel-maps of the ^{12}CO J=1→0 integrated intensity within 4 km s^{-1} velocity bins of the redshifted emission in the main flow's red lobe and the HL Tau region. The velocity range is given in each panel. The contours in each panel start at 1 K km s^{-1} (5 σ) and go in steps of 2 K km s^{-1} in panels "a" and "b" and in other two panels the step is changed to 1 K km s^{-1}. The (0,0) is at the IRS 5 location.

Fig. 8.— Channel-maps of the ^{12}CO J=3→2 integrated intensity within 4 km s^{-1} velocity bins of the redshifted emission in the main flow's red lobe and the HL Tau region. The velocity range is given in each panel. The contours in panels "a" and "b" start at 2 K km s^{-1} (10 σ) and go in steps of 5 K km s^{-1}. In the panels "c" and "d" the contour step is 2.5 K km s^{-1}. The (0,0) is at the IRS 5 position.

Fig. 9.— Position-velocity plot for L1551 IRS 5 in CO J=1→0. The left side of the plot shows the p-V plot, made along the 50° axis going through IRS 5. The width of the cut is 6 pixels or 2′.25. On the right side, is the integrated intensity image of the L1551 outflow in J=1→0 , rotated 50°. The dotted vertical lines outline the width of the p-V swath. The position of the driving source IRS 5, corresponds to the zero value on the y axis. The positions of the different HH objects are marked.

Fig. 10.— CO J=3→2 p-V plot for L1551 IRS 5. The J=3→2 integrated intensity image on the right side is rotated 50°. The width displayed in the integrated intensity image is 2′.2, while the width of the p-V cut is 1′.1 centered on IRS 5 (dotted vertical) lines.

Fig. 11.— ^{12}CO redshifted integrated intensity emission in the EW direction within 2 km s^{-1} velocity bins. The square at (0,0) position marks the IRS 5 and the cross marks HH 102 position. The contours in panel "a" start at 0.75 K km s^{-1} (6 σ) and go in steps of 0.75 K km s^{-1}. In panel "b" the step is changed to 0.125 K km s^{-1}, and the lowest contour level is 0.5 K km s^{-1}. In the top two panels, the step is 0.125 K km s^{-1} and the lowest contour is 0.25 K km s^{-1}.

Fig. 12.— CO J=1→0 p-V plot for EW flow cut along the 270° axis emerging from HH 102 (zero on the y axis). The cut is 90′ wide, and on the right side, the integrated intensity image made over redshifted velocities, and rotated 270° is shown.

Fig. 13.— Four different areas A1, A2, A3 and A4 are identified along the L1551 flow (see text for more).

Fig. 14.— Upper panels show averaged ^{12}CO J=1→0 (solid line) and ^{12}CO J=3→2 (dotted line) spectra for A1 (left panel) and A2 (right panel) regions. ^{12}CO J=1→0 data are smoothed to the 0.9 km s^{-1} velocity resolution of ^{12}CO J=3→2 . In the lower panels, the ratios of the averaged ^{12}CO J=3→2 and ^{12}CO J=1→0 spectra are displayed. The weighted mean ratio in each region is computed using only filled points, i.e. in the line wings where lines are less optically thick.

Fig. 15.— Optical depth profiles. The averaged ^{12}CO (solid line) and ^{13}CO (dotted line) spectra in A1 and A2 areas are shown in the upper panels. In region A1, for velocities larger then 2 km s^{-1}, we show spectra in full resolution, and for lower velocities, data are binned in 1 km s^{-1} bins. Similarly, in region A2, for velocities larger then 10 km s^{-1} data are binned in 1 km s^{-1} bins. The lower panels show the logarithmic fit to the ratio in the A1 and A2 regions respectively.

Fig. 16.— The mass-velocity distribution for the outflows within each area A1-A4 in L1551. The $M(v)$ distribution is plotted as log(dM/dv) vs. log(v$_{out}$) where v$_{out}$ is outflow velocity v$_{out}$ = v − v$_{LSR}$. The mass points are in velocity bins thet are uniformly spaced in log velocity (see text for more). For regions A2 and A3, we present data for both the blueshifted outflow (triangle points) and the redshifted outflow (diamond points) within these regions. The slopes of the linear fits (the power law index, γ) are indicated in the figure.

Fig. 17.— The $M(v)$ relation derived for region A2 redshifted gas by using all the data without an rms threshold (diamonds), and by setting a threshold of 3σ for the ^{12}CO emission (triangles). We show fits to both $M(v)$ relations with broken power laws.

Table 1.   Outflow Mass, Velocity and Energy estimates

T_{ex}	25 K			16.5 K		
Lobe	Mass $M_\odot$	Momentum $M_\odot \mathrm{km\ s^{-1}}$	Energy $\times 10^{43}$ (ergs)	Mass $M_\odot$	Momentum $M_\odot \mathrm{km\ s^{-1}}$	Energy $\times 10^{43}$ (ergs)
A1 B	4.25	15.65	111.5	3.28	12.09	88.33
A2 R	1.40	7.46	60.7	1.08	5.76	46.80
A2 B	0.53	1.52	6.2	0.41	1.17	4.75
A3 R	0.34	1.46	8.6	0.26	1.13	6.63
A3 B	0.23	1.06	15.6	0.18	0.82	12.02
A4 R	0.59	1.92	9.82	0.46	1.48	7.57
BT	4.54	15.66	116.7	3.50	12.08	90.01
RT	2.33	10.84	79.12	1.80	8.37	61.00
Total	6.87	26.50	195.19	5.30	20.45	151.01
AC[a]	110		85			

[a]Ambient Cloud. Mass of the ambient cloud is estimated using T_{ex} determined in each spatial point from the ^{12}CO line thick condition. See text for more.

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